DIRECT SUBNANOSECOND VOLTAGE MONITORS

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Summary

Advanced system development in the subnanosecond time frame increasingly demands high-resolution voltage measurements for both single-shot and repetitive operation. Voltage monitors having capabilities up to the hundred kilovolt level have been developed for direct measurements in discrete and transmission line geometries. Resolutions of 100 ps at 100 kV to 30 ps at 20 kV have been achieved. Detailed test data is presented and ultimate voltage scaling limits are discussed.

Direct Subnanosecond Voltage Monitors

As pulse systems progress to shorter risetimes, faster response voltage probes are required. Conventional broadband microwave techniques can be an aid in the design of better pulse instrumentation. This paper describes how some of these techniques are applied to resistor transmission line circuits. The first probe described is dedicated to a particular measurement position and may be difficult to use elsewhere because of dimensional restrictions that will become apparent.

The characteristics of an ideal voltage probe and the compromises necessary to optimize a real probe are discussed. Figure 1 shows an air-filled parallel plate transmission line with a wave front traveling from left to right. Between the conductors is a 1-in.-long cylinder having a uniform surface resistance film that is thin enough to avoid skin effect problems. Almost all materials used for high resistance films fall into this category. When the film resistance is high, the electric field lines are not appreciably distorted and the traveling wave is essentially unaffected by the probe. Furthermore, if the resistor surface is exactly parallel to the E-field lines, the wave front instantaneously establishes a uniform voltage gradient across the resistor enabling current to flow from one end of the resistor to the other with no transit time. We will assume that the resistor diameter is <1/10 of its length and its resistance is >3000 Ω.
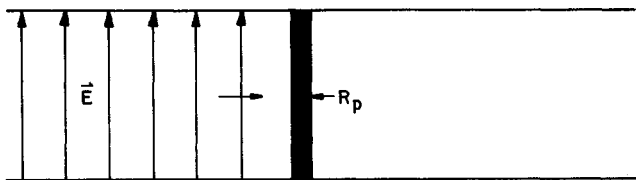

Fig. 1. Traveling wave impinging on resistor inside parallel plate transmission line.

Figure 2 illustrates how the signal can be extracted for monitoring through a coaxial connection. In this case, the voltage division ratio is simply the resistance of the divider resistor divided by the impedance of the output transmission line.

However, the film comprising the resistor must be supported by a substrate that has a dielectric constant that is higher than the surrounding medium. The most common resistor substrate is alumina, which has an ϵ_r of 9. Some other ceramics have a lower ϵ_r, while a substrate such as glass has an ϵ_r near 5.5 at the frequencies of interest.
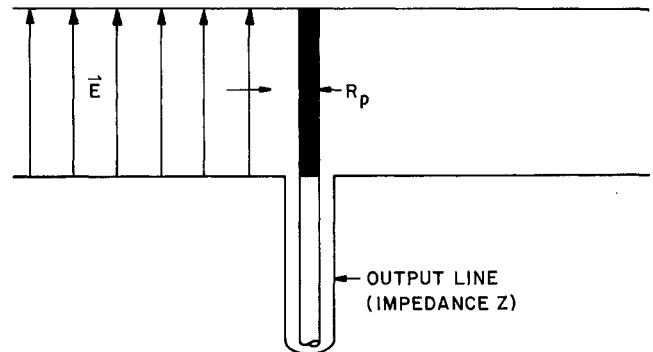

Fig. 2. Method of extracting resistor probe signal through coaxial connection.

The higher dielectric constant of the substrate adds an undesirable distributed shunt capacitance (C_p) across the film resistor (R_p), shown in Fig. 3, that causes an overshoot in the output if left uncompensated. Although this RC time constant is very short, generally picoseconds, the impulse amplitude can be very large, theoretically equal to the pulse amplitude itself. While this spike is not visible on a risetime-limited oscilloscope, a smeared overshoot may be observed. Depending on the system risetime, if the system, including the pulse to be monitored, has a long risetime, the overshoot will be considerably reduced by the effective low-pass filtering. With a system risetime of 10 ns, for example, the overshoot can be a few percent and can usually be ignored. To remove the undesired output overshoot from systems with risetimes less than 1 ns, the probe must have compensating capacitor (C_c) added to make it a capacitive divider with the same division ratio as the resistive divider. The selection of the compensation capacitor is accomplished experimentally in a test fixture because the distributed capacitance across the probe resistor is very difficult to calculate or measure directly.
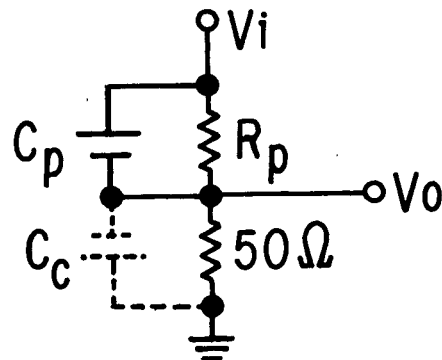

Fig. 3. Simplified equivalent circuit of resistor probe system showing distributed shunt capacitance C_p and required compensation capacitor C_c.

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Figure 4 shows a TEM test cell consisting of a microstrip type of planar circuit. This design is patterned after the Air Force Weapons Laboratory (AFWL) test cells for the Trestle Program and uses only one ground plane, making it easier to build than a strip line that has a ground plane on both sides. Some years ago Barth made a 1-m-high, 1/100 scale model of one of these test cells. Using a 1-m-long resistor as a voltage probe in the center of the test area, a pulse with a known risetime of 200 ps was accurately tracked. It appears that this is not the ultimate limit of a 1-m film resistor voltage probe. A smaller test cell has since been developed that creates a uniform voltage gradient with a very fast risetime for adjusting probe compensation.
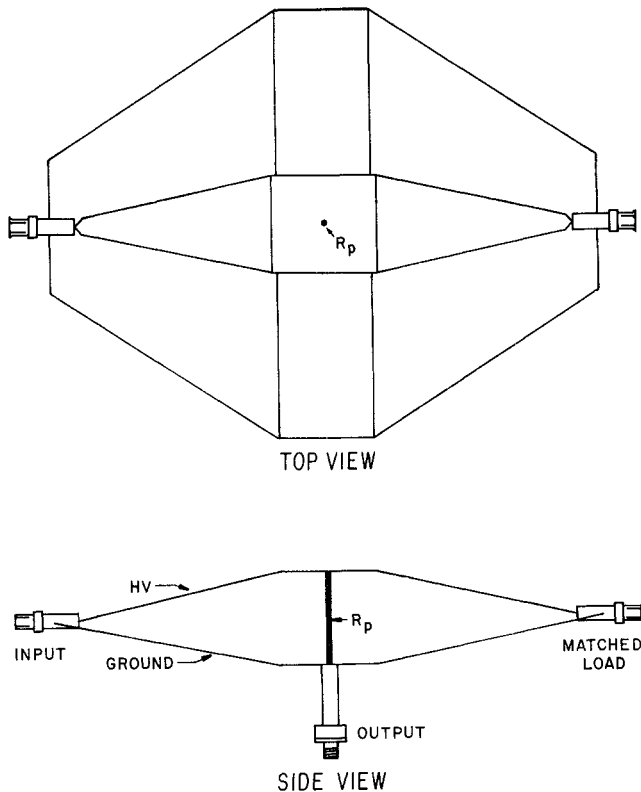

TOP VIEW

SIDE VIEW

Fig. 4.   Schematic of TEM test cell developed for resistor probe compensation.

A sampling scope and a 200-V subnanosecond pulse generator are used when testing the response of a voltage probe. The compensating capacitor is adjusted for the best risetime with minimum overshoot. The output response is compared to the response through the interconnecting cables so that cable losses are subtracted.

One design of the compensation capacitor found to be very effective is shown in Fig. 5. For subnanosecond response, the compensation capacitor must be a very pure capacitance with low parasitic reactance. The coaxial construction of this type of capacitor is of a type used in microwave filters and is readily constructed. This compensation capacitor design works exceptionally well if the dielectric material is thin and the length "ℓ" of the compensating section is short. However, if this section is an electrical half-wave length of frequency components present in the traveling wave, undesirable ringing of the probe output will result. While not the most theoretically ideal compensating capacitor, it can be used to at least 100-ps
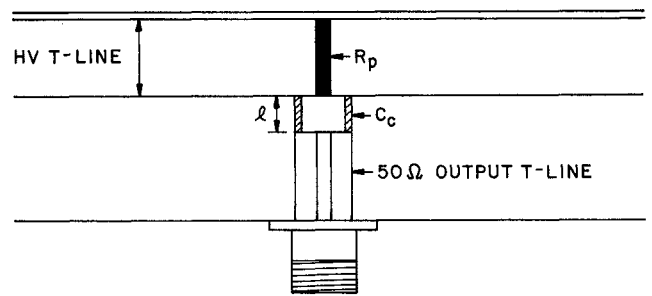

Fig. 5.   Schematic of hollow, coaxial compensation capacitor (C_c) with wall thickness much less than the diameter of output transmission line.

response times. Physically, it is a very practical design that provides a centering support if the output transmission line is long while it presents a very small physical as well as electrical disturbance to an experiment.

There is, of course, the average power constraint (watts/unit area) on the probe resistor surface that must be considered when employed in a high repetition-rate system. Depending upon the medium surrounding the resistor, its thermal transport properties, and the temperature coefficient of resistance of the film, the probe should be designed to not change resistance appreciably during operation. If the power dissipation is excessive or if the pulse energy exceeds the film's fusing limits, then the resistance path length must to be increased by spiraling of the film.[1] The distributed capacitance of a spiraled resistor is much higher than an unspiraled resistor, and the required compensation capacitance is, therefore, also higher.

The voltage coefficient of resistance is another problem with resistors where high-voltage gradients are applied. The voltage coefficient is the fractional change of resistance per unit applied voltage and may change as the voltage is increased. Most resistors show decreasing resistance with increasing voltage. The circuit used to measure the voltage coefficient is described elsewhere.[2]

Placing a resistor between the high-voltage point to be measured and the ground plane parallel to an E-field line enables a probe to be constructed with the best possible response. Where the resistor cannot be placed in the field directly, a portable probe is required.

Laboratory Probes for emf Measurement with Minimum Circuit Loading

Numerous applications of subnanosecond high-voltage generators, such as drivers for electro-optical streak cameras[3] and Pockels' cell optical modulators require a reliable probe type of voltage measurement system. Subnanosecond high-voltage attenuators have been described by several authors and are suitable for measuring pulse amplitudes up to 5 kV.[4-6] In the case of fast laser light modulators and switching systems,[7] operating at voltages of the order of 15 kV, a probe-type voltage measuring system having minimum circuit loading is generally required for developmental diagnostics as well as continuous monitoring of the shape of ultrafast voltage pulses having subnanosecond risetimes and falltimes. Furthermore, it is often desirable that the probe be of a shielded type and still offer a minimum of circuit perturbation for point source voltage probing in low-impedance (50-Ω) systems.[4-7]

With these requirements in mind, an inexpensive probe has been developed for laboratory construction using standard components, permitting multikilovolt nanosecond pulses to be measured in conjunction with commercial 50-Ω attenuators[8] and oscilloscopes. This system was specifically designed for small perturbation voltage measurements of the high-voltage pulses associated with laser instrumentation. The probe, for frequencies below 50 MHz, essentially has a resistive input impedance of about 3000 Ω. For fast-pulse risetimes, this reduces to the surge impedance of the distributed ferrite-loaded transmission line.[9-11] Reflections on this line, whose surge impedance is about 300 Ω, are absorbed by the resistive component of the ferrite impedance,[10-11] resulting in only small perturbations of the test point voltage.

Probe Design

The voltage probe was constructed using a carbon composition resistor placed inside a modified HN series high-voltage cable connector type UG-60A/U, as shown in Fig. 6. System overshoot was effectively dampened by introducing a series loss term into Z_i shown in the simplified equivalent circuit of Fig. 7. Here, Z_i is the surge impedance of the input transmission line from the test point to the main body of the probe. For a short 2-cm-wide ground braid placed ~6 cm from the ferrite beads, Z_i is approximately 300 Ω.[11-12] The impedance of the resistive portion of the transmission line, Z_r, is represented only approximately by the shunt capacitance C_1 across the resistance element of R_1, with C_2 being the capacity of the resistor to the probe housing.[5] The limitations of this model for short pulses are recognized,[1,2,10,11,13] and they are presented only to illustrate the general reasoning behind the experimental compensation approach adopted.

At high frequencies, the equivalent line impedance for Z_r, if R_1 was 0 Ω, would be about 25 Ω, indicating that there would be a substantial reflection back toward the source.[11] In order to reduce these reflections and their subsequent perturbation on the system being measured, a distributed resistive loss was introduced into Z_i. Ferrite beads of type 4B material, substantially resistive from 10 MHz to at least 0.5 GHz,[14] were inserted onto the center wire (nine in all) until
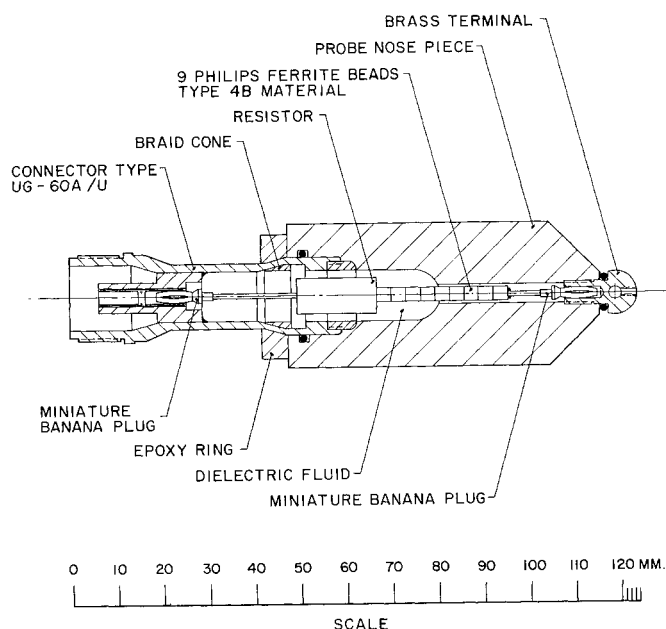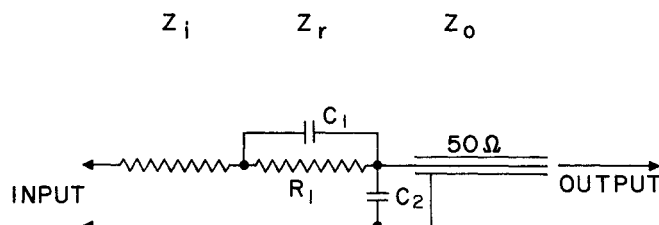
Fig. 7. Simplified equivalent circuit for high-voltage probe.

a minimum overshoot was observed in the probe system pulse response. The details of the probe fabrication are presented elsewhere.[15] Briefly, R_1 was adjustable in position inside the connector, thus permitting fine adjustment of the two time constants R_1C_1 and Z_0C_2 to minimize the variation of the attenuation factor with frequency. The resistors used were Allen Bradley type HB, 2-W, 3 kΩ carbon composition. The probe insulating medium was Dow Corning type 200 dielectric fluid (viscosity, 20 cS).

Risetimes and Falltimes

The transient response and risetime of the probe, complete with 1 m of RG-8/U coaxial output cable, were measured at subkilovolt voltage levels. A source voltage test point was provided at the midpoint of a terminated 0.5-m length of RG-8/U cable by soldering a small banana plug to the center conductor. Using a Tektronix random sampling system, there was no detectable difference (± 5 ps) between the rising edge of the test signal at either end of the cable when the probe was connected to the tap point. A short ground braid ~2-cm-wide connected the body of the probe to the outer braid of the coaxial cable. The location of the probe and ground braid did not have a significant effect on the pulse shape until the braid directly contacted a substantial portion of the nose of the probe. The probe system risetime (complete with its 1-m output cable) was inferred by assuming the leading edge to have a Gaussian shape.[16] For a sample size of 12 units the average risetime was 26.9 ps with a 3 σ of 6.2 ps. Thus, at the 99% confidence level, the risetime is less than 33 ps for a rather large sample of probes.

In addition, the absorption characteristics of the ferrites and the small input capacitance of the probe have minimized the stored charge degradation of pulse falltimes.[1-2] Figure 8 shows a recording of the rising and falling edges of a 1-kV pulse from a coaxial reed pulser on a time scale of 2 ns/div. From the recorded falltime of the probe output, one concludes that truncated pulses can be recorded with an oscilloscope limited resolution of ~100 ps.
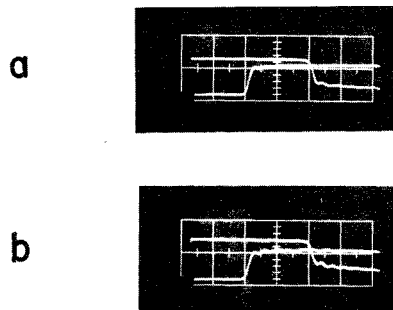
Fig. 6. Cross-sectional view of subnanosecond high-voltage probe.

Fig. 8. Oscillograms showing leading and falling edges of probe input voltage (a) and output voltage (b) at sweep speeds of 2 ns/div.

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Peak-Voltage Capability, Linearity, and Stability

These factors were evaluated by using a fast thyratron pulser capable of supplying pulses of up to 40-kV amplitude, at a width of 100 ns (FWHM), for repetition rates varying from single shot up to 60 Hz. The voltage applied to the probe system under test was monitored with a modified Tektronix P6015 high-voltage probe ($\tau_r \sim 2$ ns). The probe linearity observed for voltages up to 5 kV was within 5%, increasing to 20% at 15 kV. Note that the voltage coefficient of the Tektronix probe was not compensated for, and thus these numbers are conservative.

Because the long-term stability of such resistive devices when subjected to substantial peak powers is of considerable importance, accelerated life tests were carried out by applying various amplitude voltage pulses of the same 100-ns (FWHM) length to several 3-kΩ resistors. The thyratron pulser was operated at 60-Hz and each resistor was subjected to a 60-s test duration at a specific peak voltage. The resultant permanent percentage resistance change in each resistor was measured immediately and again 12 h after test and is plotted in Fig. 9. Voltages of up to 10 kV caused <0.1% permanent resistance change, suggesting that for long-term stability, a safe working voltage limit is 10 kV. Although a larger permanent resistance change ($\sim 0.5\%$) was observed at 20 kV, infrequent use of the probe system at such voltage levels has not presented any difficulties. Short-pulse damage may well be predominately due to voltage-stress-induced breakdown inside the resistor.[17-19]

Long-Pulse Performance and Shielding

The probes were tested at subkilovolt voltages and found to exhibit aberrations of less than $\pm 1.5\%$ on the pulse top for pulse lengths out to dc. At higher voltages, similar performance has been observed for pulses up to 100 ns in length. When the plastic part of the probe was wrapped in aluminum foil for additional shielding the probe risetime increased to 250 ps.

Pickup of extraneous EMI was evaluated by operating the probe without the aluminum foil directly on top of a parallel-plate transmission line Pockels' cell.
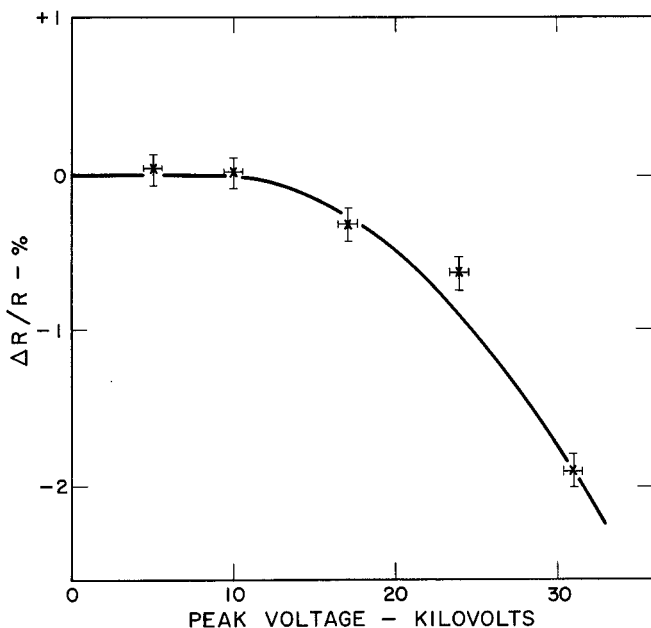

Fig. 9. Plot of permanent resistance change versus peak applied probe voltage.

Operating at 6-kV pulse amplitude and 120-ps risetime, the signal-to-noise ratio (probe connected/probe disconnected) was in excess of 30 dB for an oscilloscope bandwidth of 1 GHz.

Repetitive Pulse Operation

The ferrite-compensated, resistive, high-voltage probe system described in the preceding sections has a measured low-level risetime of less than 33 ps. When used in conjunction with a Tektronix 519 oscilloscope, this voltage probe system provides a reliable scope-limited measuring system for moderate repetition rate, multikilovolt pulses at point sources in low impedance circuitry. In addition, the system has been employed to measure repetitive high-voltage pulses from a few Hz to ~120 Hz for on times of several minutes. At the higher repetition rates, for a 100-ns FWHM pulse width, the average power for a 15-kV pulse amplitude is about 1 W, which is within the dissipation capability of probe.

Preliminary measurements showed a stability in this case of $\Delta R/R$ of -2.5×10^{-6}% per pulse. Evaluation of the accumulative long-term stability for this mode of operation requires additional test data. For high-repetition-rate operation and maximum stability the film resistor probes described are more appropriate.

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